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and the (true) radial wind velocity. We use turbulent fields computationally generated by means of a large- eddy simulation to quantify this effect. We show that these biases may amount to several tens of centimeters per second in the atmospheric boundary layer, which is consistent with the biases observed with vertically pointing boundary-layer radar windprofilers.

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Using large-eddy simulation to investigate intermittency fluxes of clear-air radar reflectivity in the atmospheric boundary layer

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***Abstract*—Clear-air Doppler radars, also known as clear-air radar windprofilers, have been used for decades to remotely monitor wind velocities in the troposphere, stratosphere, and mesosphere. The traditional assumption is that the Doppler velocity (the first normalized moment of the Doppler spectrum) is an unbiased measure of the radial wind velocity within the radar's observation volume. Here we show that "intermittency fluxes", i.e., covariances of the turbulently fluctuating clear-air radar reflectivity and the turbulently fluctuating radial wind velocity, lead to systematic differences between the Doppler velocity and the (true) radial wind velocity. We use turbulent fields computationally generated by means of a large-eddy simulation to quantify this effect. We show that these biases may amount to several tens of centimeters per second in the atmospheric boundary layer, which is consistent with the biases observed with vertically pointing boundary-layer radar windprofilers.**

I. Introduction

Since the 1970s, clear-air radars, also known as radar windprofilers, have been used to remotely probe wind and turbulence characteristics in the troposphere, stratosphere, and mesosphere [1] [2] [3] [4] [5] [6]. Radar windprofilers exploit the very weak but still observable UHF and VHF radio waves backscattered from turbulent refractive-index perturbations in the optically clear atmosphere. The theory of acoustic and electromagnetic wave propagation through the turbulent atmosphere had been pioneered by Tatarskii [7] [8].

In the 1980s and 1990s, after radar windprofilers had reached a certain maturity, biases in the Doppler velocities observed with vertically pointing profilers were reported that could no longer be attributed to instrumental deficiencies. Instead, evidence accumulated that such biases were caused by certain correlations between wind velocity fluctuations and reflectivity fluctuations [9] [10]. Those mechanisms, however, relied on the presence of gravity waves [9] or Kelvin-Helmholtz billows [10] and therefore could not account for the velocity biases of a few tens of centimeters per second that Angevine [11] observed within the convective boundary layer. Observational and theoretical aspects of those Doppler velocity biases have been discussed in more detail in [12] and [6].

Around 1970, the large-eddy simulation (LES) technique was pioneered by Lilly [13] and Deardorff [14]. LES is now the method of choice for computationally investigating the structure and dynamics of the atmospheric boundary layer, and LES experiments may be considered in many respects to be equivalent, if not superior, to real-world boundary-layer experiments [15].

In 1999, we used for the first time LES-generated fields to synthesize realistic clear-air radar signals [16]. The main motivation for that study was to reproduce Angevine's [11] observations of velocity biases in the convective boundary layer.

II. Intermittency in atmospheric turbulence

Classical turbulence theory [17] [18] and the classical theory of wave propagation through the turbulent atmosphere [7] [8] rely on the assumption that turbulent dissipation rates and turbulent structure parameters may be treated as deterministic quantities that vary only slowly in space and time. In their two 1962 landmark papers, however, Kolmogorov [19] and Obukhov [20] showed that at high Reynolds numbers as encountered in the atmosphere and the oceans, dissipation rates have to be treated as random variables and that the statistics of that intermittency has to be accounted for in a complete theory of locally homogeneous turbulence.

III. Intermittency fluxes and Doppler velocity biases

The Doppler velocity v_D is the first moment M_1 of the Doppler spectrum, normalized by the zeroth moment. Assuming that the profiler points in the vertical direction and interpreting the Doppler spectrum as a histogram of reflectivity-weighted radial (here vertical) wind velocities, we can write

$$v_D = \frac{M_1}{M_0} = \frac{\langle \eta w \rangle}{\langle \eta \rangle}, \tag{1}$$

where w is the vertical wind velocity and η is the clear-air volume reflectivity. Now, we treat η and w as random variables and write them as sums of mean value and fluctuation:

$$\eta = \langle \eta \rangle + \eta', \qquad w = \langle w \rangle + w'. \tag{2}$$

This gives

$$v_D = \frac{\langle\eta\rangle\langle w\rangle + \langle\eta' w'\rangle}{\langle\eta\rangle} = \langle w\rangle + \Delta w, \quad (3)$$

where

$$\Delta w = \frac{\langle\eta' w'\rangle}{\langle\eta\rangle} \quad (4)$$

is the velocity bias.

Note that $\langle\eta' w'\rangle$ may be interpreted as a turbulent clear-air reflectivity flux. We suggest to refer to such a flux as *intermittency flux* because in traditional propagation theory [7] [8], which does not account for intermittency and which treats η (which is proportional to C_n^2 [7]) as a deterministic variable, $\langle\eta' w'\rangle$ is always zero.

IV. Using large-eddy simulation to compute intermittency fluxes

We used a large-eddy simulation similar to the one in our previous study [16], where we assumed that the dwell time is short compared to the large-eddy overturning time scale and that the radar's observation volume is small compared to the energy-containing scales in the convective boundary layer. In the previous study, we did not find a significant velocity bias. In the current study, however, we allowed the effective radar sampling volume to be large compared to the large-eddy scale, and we find velocity biases with magnitudes of up to 50 $\mathrm{cm\,s^{-1}}$ (see Fig. 1), consistent with Angevine's [11] observations.

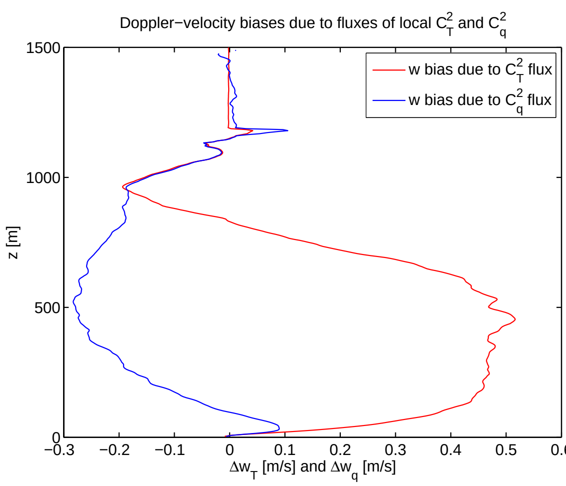

Fig. 1. Vertical profiles of Doppler velocity biases caused by intermittency fluxes of the temperature structure parameter, C_T^2, and the humidity structure parameter, C_q^2, respectively. The profiles were computed from an LES-generated convective boundary layer similar to the LES described in our previous study [16].

V. Summary and conclusions

"Intermittency fluxes" of clear-air radar reflectivity can lead to Doppler velocity biases observed with vertically pointing radar windprofilers in the convective boundary layer (CBL). We have used the large-eddy simulation (LES) technique to computationally generate a CBL, and we computed vertical profiles of Doppler velocity biases that agree qualitatively and quantitatively with biases observed in field measurements.

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